Modeling and Uncertainty Quantification of Particulate Composite Materials

Project Proposal

David W. Allen, Miles A. Buechler, Anthony D. Puckett
{dallen, buechler, apuckett} @ lanl.gov
WT-2: Analysis & Prediction, Los Alamos National Laboratory
Los Alamos, NM 87545

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Abstract

Particulate composite materials represent a growing material class which blend the strengths (and weaknesses) of their parent materials. Examples of these materials include plastic-silica engine parts, plastic-wood construction materials, solid rocket propellent, and some explosives. These materials are becoming integrated into civil and mechanical structures in critical load paths. Advanced computer simulations are commonly being used in engineering to when, how, and why structures will fail. Before such materials can be used in advanced structural simulations, however, their dynamic responses must be investigated, modeled, and validated over the intended design space. This project proposes to investigate dynamic behavior of the particulate composite material *sugar mock* under varying loading and thermal conditions over three possible frequency ranges of interest: below 1Hz, 1Hz to 20KHz, and>>20 KHz through experimentation and modeling.

In the end, models for the different frequency ranges will be presented with associated sensitivity and uncertainty in the parameters. These models and associated information are the first tier in the *Bottom-Up* approach to model validation. With a validated material model, more complex system models can be constructed with confidence and used for structural health monitoring and damage prognosis to predict remaining life or operating limits for the system.

Introduction

Particulate composite materials represent an interesting material class which blend the strengths (and weaknesses) of their parent materials. For example researchers at Ohio State University have proposed using particulate composite materials of plastic and Silica for producing heat-resistant, tough, yet light engine parts. New building materials are being sold which are particulate composites of wood embedded in a plastic matrix for outdoor construction. Solid rocket propellents, and some forms of explosives also fall into this material category. Before such materials can be used in advanced structural simulations, however, their dynamic responses must be investigated, modeled, and validated. This project proposes to investigate a non-hazardous mock polymer bonded explosive (known as sugar mock) under varying loading and thermal conditions over a range of time scales. Of particular interest is the long term creep behavior,which is influenced by the particulates, the matrix, and the interaction between the particulates and the matrix.

The goal of this project is to determine the appropriate creep model and material constants to model the sugar mock and quantify the uncertainty of the model.

Theory

The time dependent elastic response of many materials is a function of temperature and time only. In the instance of creep, the application of a constant load produces an increasing strain that is a function of time. At an elevated temperature the strain will follow a different time dependent path. For particulate composites, a stress dependence has also been observed.

There are a variety of models in the open literature that express the creep strain as a function of time, temperature, and stress. An example of one of these models is:

$$\epsilon_c = e^{A/T} * t^n * \sigma^m \tag{1}$$

where ϵ_c is the creep strain, T is temperature, t is time, σ is stress, and A, n, and m are constants. Other functions are possible, so a portion of the project will be determing suitable material models that capture the experimental data.

The creep behavior of a material represents the long term response. The response of the material at shorter time scales is also of interest but requires different experiments and probably different material models.

Experimental Work

In an effort to characterize the response of a particulate composite over several time scales several experiments will be performed. These experiments can be cataloged by their target time scale. Creep experiments will characterize the material at very low frequency (below 1Hz), impact experiments characterize the medium frequency (1Hz to 20 KHz), and ultrasonic experiments characterize high frequency (>>20KHz) responses. Some initial experiments will be performed and the students will use the results to perform an intelligent design of experiments (DOE) the goal of which is to fully characterize the material. Rigorous analysis of experimental uncertainty will be undertaken and is essential for the final validation of the material model.

Design of Experiments

Given the limited amount of time, the number of experimental setups possible, and the large design space (loading, temperature, time scale) it will be beneficial to perform a design of experiments. A DOE provides an analytical way of choosing which variables to perturb independently, or in combination and optimizes the number of tests required to fill a design space. The data collected will help determine how sensitive the output is to a particular input or interactions of the inputs. The DOE will also take into account replication to capture variation between tests.

Proposed Experiments

- Compression experiments may be performed which involve applying an ideally uniform stress to the compression sample. Because the compression experiments result in a uniform stress and strain distribution the data analysis is relatively simple; however, the samples will be much stiffer in this mode than in other experiments which may reduce the signal to noise ratio

- Deflection of cantilever beams may provide much better signal to noise ratio, though the non-uniform distribution of stress and strain can complicate the data analysis.
- Torsional experiments my also be performed providing a reasonable trade off between signal to noise ratio and data analysis methods.
- Impact experiments will be performed and both frequency domain and time domain data analysis methods may be employed to characterize medium frequency dissipation of energy in the material.
- Ultrasonic transducers will be employed characterize the material dissipation at very high frequencies.
- Care will be taken to record variation in loads, temperature, and material dimensions to capture uncertainty in the experiments.

Sensitivity and Uncertainty

Often times a model is fit to a subset of experimental data, then it is compared to a new set of experimental data and fails miserably. This failure could be because of a poor choice in models, or the model is perfectly adequate but because there exists a sensitive parameter or uncertainty was not quantified, the resulting prediction can be poor. The first part, *Sensitivity analysis*, is the study of how the variation in the output of a model can be apportioned to different sources of variation in the input or system.

Another large part of using a model for prediction is quantifying the uncertainty in the model inputs. This uncertainty is then propagated through the model to provide a bounded output. For example, instead of reporting a predicted displacement as $d = 1.0mm$ (a very bold statement), displacement is reported as an interval ($d = [0.8, 1.2]mm$) or probabilistically ($\bar{d} = 1.0 \pm .2mm$). This variation in the displacement can come from several sources of uncertainty:

- **Measurement Uncertainty:** A material model typically depends on a fit to some experimental data. Measurement equipment is not infinitely precise, therefore the model should reflect this uncertainty in the data.
- **Stochastic Uncertainty:** The effect of random events on the outcome of your data. This uncertainty is often attributed to environmental conditions over which there is little control (humidity, temperature, wind loading).
- **Epistemic Uncertainty:** The uncertainty in knowledge. This uncertainty can be attributed to "expert judgement", "lack of knowledge", and other non-probabilistic sources of uncertainty. For example, if three experts state that the modulus for aluminum is 70.0, 71.5 and 74.0 MPa respectively, this is not random, nor explicitly measured, it is epistemic.

Summary

Over the course of the summer several experiments on sugar mock will occur to collect data for characterizing a suitable material model. This model will will account for the material time dependance in several frequency ranges. Consideration will be given to sources of uncertainty and their affect on the model response. The model will be rigorously validated and the valid frequency domain(s) will be identified. If time allows, experiments will be performed in a failure region for a given test structure.

References

Familiarization with the following terms and concepts is necessary. More in depth and specific literature will be made available as the summer approaches.

Wikipedia Keywords (`http://www.wikipedia.com`):
Creep Deformation
Time Temperature Superposition
Wave Propagation
Design of Experiments
Sensitivity Analysis
Uncertainty

Schedule

Week 1	Introduction to LADSS, Paperwork Literature Review Familiarization with test setup Laboratory Inspections
Week 2	Introduction to Design of Experiments Introduction to Modeling
Week 3	Design of Experiments Selection of candidate models
Week 4	Start experimentation Quantification of experimental uncertainty
Week 5	Continue experimentation
Week 6	Sensitivity analysis Continue experimentation Begin uncertainty propagation
Week 7	Continue Analysis Begin Presentation Begin Final Editing
Week 8	Finish Presentation Finish Final Editing

Table 1: Proposed Work Schedule for the summer of 2007